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Estimation of the reflection and absorption of solar radiation by a cloudless atmosphere from recordings at the ground, with results for Kew Observatory

by

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Summary

Records of the total and diffuse solar radiation received on a horizontal surface, the illumination of a horizontal surface, the intensity of the direct solar beam for the whole spectrum and for two spectral regions defined by filters, and the duration of bright sunshine, have been made at Kew Observatory during various periods since 1946. The results are compared with those to be expected from an extraterrestrial distribution of solar radiation recently proposed by Nicolet (1951a, 1951b) and the known attenuation of an unpolluted atmosphere.

The mutual consistency of the various observations is demonstrated and a small correction to the illumination measurements is proposed. The additional absorption and scattering of the cloudless atmosphere at Kew are computed, and its albedo deduced.

1. Introduction

Continuous records of solar radiation and illumination have been maintained for some years at Kew Observatory, and the work to be reported was begun as an investigation of the mutual consistency of these records. It soon became clear that, at least as regards the means of large numbers of readings, this consistency was greater than had been expected, and that by comparison of the different elements useful results on the absorption and reflection of the atmosphere could be extracted. Whilst the precision of the results is clearly not high, a study of recent work on atmospheric albedo, particularly that of Fritz (1951) suggested that even approximate estimates would be useful, owing to wide divergence of the values accepted by different workers in the quite recent past. The atmospheric albedo for a single locality is not of itself of general interest, but the recording of various components of the solar radiation is in progress at an increasing number of stations widely distributed over the earth and a method of estimating albedo from the records of such stations would provide a valuable addition to the methods available for estimating the planetary albedo. In this report we restrict ourselves to cloudless conditions; we hope to extend some aspects of the work to average and overcast conditions at a later stage.

There is one direction in which the results obtained at Kew have a specific interest, although being at the same time of less than the normal value in the general meteorological problem of the energy balance. Kew is situated in an industrial area, with pollution sources rather sparse to the south and southwest, moderate to southeast, west, and north, and with the bulk of the London source between east of north and south of east. Some effects of smoke are almost always visible to the eye; with easterly winds they are often quite spectacular. A qualitative indication of the effect of change from light westerly to light easterly winds is given by Fig.1.

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2. The material used.

(i) Available observations.

The following records, which are made on a routine basis at Kew, have been used in this investigation. The majority have been, or will shortly be, described elsewhere, and only those details essential to the present study are given. The records will be referred to by the abbreviations which are indicated in brackets.

(a) Total solar radiation on a horizontal surface (T), by Moll-Gorczynski solarimeter and recording galvanometer ("Cambridge" thread recorder) (Blackwell 1954). Records for the years 1947-1951 inclusive have been used.

(b) Diffuse solar radiation on a horizontal surface (D), by the same means as T, with the direct radiation of the sun obscured by an annular shade, mounted on a polar axis, and subtending an angle varying with time of year between about 8° and 12° at the centre of the thermopile. The reading is "corrected" for the effect of the sky obscured by this ring on the assumption (obviously erroneous) that the diffuse radiation is uniform over the sky (Blackwell 1954). Records for the years 1947-1951 inclusive have been used.

(c) Solar intensity, i.e. flux of solar radiation in the direction of the solar beam (I) by Moll thermopile with aperture limited by diaphragms, mounted on a heliostat, recording in the same way as T and D. The difficulty of specifying precisely the effective aperture of such an instrument has been discussed at length by Bossy and Pastiels (1948). For the present purpose it must suffice to say that the angle subtended at the centre of the thermopile by the diameter of the diaphragm limiting the area of sky "seen" from that point is 10°, and that there is a "penumbral" zone of about twice this diameter (Stagg 1950). Selected records in the period March 1948 to June 1949 have been used.

(d) Intensity of solar radiation transmitted by a Chance filter OY2 about 2 mm. thick (I_Y). The instrument is similar to that used for I with the addition of the filter. The transmission of the filter was determined by spectrophotometry at the N.P.L., and is shown in Fig.2. Records in the period September 1947 to September 1948 have been used. Routine recording ceased in March 1949.

(e) Intensity of solar radiation transmitted by a Chance filter O.R.1 about 2 mm. thick (I_R). The instrument was identical with that used for I_Y, being mounted on the same heliostat. The transmission of the filter, determined at the N.P.L., is shown in Fig.2. Records in the period September 1947 to June 1949 have been used. Routine recording ceased in November 1949.

(f) Total illumination of a horizontal surface (vertical luminous flux) (L), by means of a selenium photocell corrected by filter to have the response of the I.C.I. normal eye (photopic vision). Blackwell (1953) has described this instrument and discussed the adjustment of the tabulations to allow for all known systematic errors. Blackwell's tabulations for the period 1947-1951 inclusive have been used.

(g) Duration of bright sunshine (S), by Campbell-Stokes recorder exposed and read in the manner laid down in the Meteorological Observer's Handbook.

For the present purpose we required values for "cloudless" occasions only. In the case of T, D, and L these were selected in the manner indicated by Blackwell (1953), all cases occurring in the period 1947-51 being included. The main criterion of "cloudlessness" was the appearence

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of the record. This does not exclude cloud at some distance from the sun, but effects of this were minimised by ignoring the first and last hours of each "cloudless" spell. In the case of I, I_Y, and I_R many readings obtained during cloudless intervals of less than 1 hour have been used; if cloud is not actually covering the sun its effect is confined to the diffuse radiation.

(ii) Errors of observation.

The use of actinometric measurements to give information on scattering and absorption in the atmosphere has long been advocated by Ångström (1951), and probably the most impressive work in this connection is that of Schuepp (1949). Such work is based on comparatively few measurements made in chosen conditions with great precision. The material we have used is of an entirely different character, being the tabulations of continuously recording instruments, made as part of the Observatory routine with no one application in mind. The precision of these measurements is treated at some length by Blackwell (1953, 1954); we mention here some relevant features with a minimum of discussion.

The tabulations comprise the estimated hourly values read, necessarily rapidly, from the thread recorder charts, and we will use both single hourly readings and means of large numbers. A single reading in cloudless conditions may be in error by 3% to 5% with high sun and 10% or more with low sun, due to incorrect estimation of the mean by the tabulator. This error is known not to be systematic and is probably negligible for means of large numbers of hourly values.

The tabulations of I, I_Y, and I_R, may be low because of incorrect alignment of the heliostats in the period between inspections (at least twice daily). This error will not be present in most of the single observations, but is almost certainly present in the means of large numbers. It would probably be seen and the reading excluded from tabulation if it became more than 10% in a single hour, but smaller errors are difficult to detect and a mean might be low by about 2%. Another systematic cause of low readings is the collection of dirt on glass domes and filters, affecting all instruments. These surfaces should be cleaned at all inspections, but are no doubt neglected occasionally, and at times an appreciable deposit collects even between inspections. This error, on single readings and means, is probably less than 1%.

There is a small systematic error in the readings of I_Y and I_R which has not been removed and which acts in opposition to those just mentioned. In use the thermopile (X, Fig.3) is protected by a layer of clear glass (Y) behind the filter (Z). Incident radiation is reflected from Y and Z in the manner shown in Fig.3. Reflection from the filter at A is included in the transmission data of Fig.2 and is allowed for in use. The thermopile is standardised with Y in position and the filter removed; reflection from Y (at B) is allowed for, but not re-reflection from the filter at C. The tabulations are therefore in excess by this amount, which is about 0.7% of the incident radiation.

Errors of L due to cosine law deviations and the temperature coefficient of the instrument are quite large. They have been removed from the mean tabulated values (Blackwell 1953) but it is not possible to do this retrospectively for individual hourly values, and we have used only means of L. Blackwell estimates that these means are correct within $\pm$ 5%, including the uncertainty of standardisation (2%) discussed below. No attempt has been made to correct T and D for cosine law and temperature coefficient errors. In the main these would affect the readings in opposite directions (standardisation is normally carried out near noon in summer, and the temperature coefficient is negative), and they are in any case much smaller than the corresponding errors of L. The effect on individual values is probably small except for low solar elevations (say 15°).

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On the whole the systematic errors so far discussed tend to reduce the tabulated T and D below the true values. This is counteracted by an effect which, whilst not an error of measurement, has the character of one for our present purpose. D, and in consequence T, as properly defined, includes radiation which has been reflected at the earth's surface and re-reflected by the atmosphere. In what follows we shall require the total and diffuse radiation transmitted by the atmosphere without regard to surface effects. Computation of the re-reflected component is not straightforward. The total albedo of the grass-land immediately surrounding Kew Observatory is rather more than 20%, that of a wide area of the surroundings must be rather less than this. The ground albedo for radiation in the visual range is estimated as less than 10%. The ground albedo is therefore highest in the infra red, where the atmospheric albedo is low, and lowest where the atmospheric albedo is high. Anticipating results to be presented later (Section 6) we may estimate the "re-reflected" component of D and T as 1% to 2% of T, and for our purpose we must regard D and T as being systematically high by this amount. In view of all the uncertainties we have set this against the opposing errors due to dirt, cosine law deviations, and shade ring "corrections", and used the tabulated values of D and T as the diffuse and total radiation transmitted by the atmosphere. We have however applied an adjustment of about 2% for this effect to L, since other systematic errors have been removed from L by "correction".

(iii) Standardisation of the records.

The relation of the Kew sub-standard radiometer to the radiation scales in common use has been discussed by Eldridge (1952). All the records (except of course L) are standardised ultimately by reference to one of the substandard Ångström pyrheliometers, and the tabulations are in terms of the "uncorrected" Ångström scale. The precision of a single standardisation is estimated as between 1% and 2%, but the errors are not systematic and long period means of the calibration factors have been used in preparing the tabulations. The Ångström scale is a little low (we shall assume a value of 1%) in comparison with the radiation scale established at the N.P.L., which agrees closely with the Smithsonian scales of 1932, 1934, 1948. The other scale in common use in meterological literature, the Smithsonian scale of 1913, is about 3% high in comparison with the Ångström scale. There is some doubt as to the precision of these comparisons, they may be in error by ± 0.5% (see e.g. Guild 1937).

The photometric readings (L) are standardised by means of lamps standardised in their turn at the N.P.L. (Blackwell 1953). The accuracy is stated by the N.P.L. to be ± 2%, and redeterminations lie within these limits.

(iv) The extraterrestrial radiation and illumination.

The general plan which we will follow is to start with radiation outside the atmosphere and to attempt to account for all losses in transmission in order to arrive at the observed value at the ground. A knowledge of the magnitude of the extraterrestrial radiation and illumination is therefore the first essential.

After some preliminary work with the specification of extraterrestrial solar radiation given in Smithsonian Meteorological Tables 6th Edn. p.416*, we decided that more coherent results were likely to be obtained with the specification given by Nicolet (1951a, b), and we have used this throughout. Nicolet's value of the solar constant is 138 mw cm^{-2} (1.98 cal cm^{-2} min^{-1}), on the Smithsonian scale of 1932-34-48, differing considerably from the value of 1.94 cal cm^{-2} min^{-1} on the Smithsonian scale of 1913, which has been generally accepted for many years. The two specifications differ mainly in the ultra-violet and infra-red regions.

Having decided on a specification of the extraterrestrial radiation it is possible to compute the extraterrestrial luminous flux. If I_λ is the

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*Footnote. This edition will be referred to below as "Smithsonian Tables".

solar intensity at wavelength λ, y_λ the relative sensitivity of the ICI standard eye at this wavelength, and K the maximum attainable luminous efficiency, we have

$$L = K\int_\lambda I_\lambda y_\lambda d\lambda \qquad (1)$$

K may be computed by appeal to the definition of the photometric standard, a black body at the temperature of freezing platinum; its value depends only on the values used for the constants in Planck's radiation formula and for the temperature of the Platinum point. We have used the figure of 680 lumens $watt^{-1}$ given in Smithsonian Tables p.449, and combined with Nicolet's data this gives 142 kilolux as the extraterrestrial luminous flux along the solar beam at mean solar distance. (The Smithsonian solar data give 138 kl.). It is of interest to note an abstract of a paper by F.S. Johnson (1954) suggesting a value of 2.00 ± 0.04 cal cm^{-2} min^{-1} on the "Smithsonian scale as explained in 1952", and a corresponding extraterrestrial illumination of 136.7 kl. The abstract does not give sufficient detail to investigate the differences in the computed luminous flux; the solar constant is close to Nicolet's but the spectral distribution is not specified in detail. Nicolet expressed great confidence in his relative spectral variation, but says that the absolute value may be in error by as much as 5%. This uncertainty is of course repeated in the corresponding illumination but it is not increased except in so far as the constants of Planck's equation and the Platinum freezing point are in doubt, since the computation of the illumination follows from the definition of the international standard of photometry. Our radiation measurements, on the Angstrom scale, are probably 0.5 to 1% low relative to the scale on which 138 mw cm^{-2} is accepted as the most probable value of the solar constant. Our illumination measurements are tied to the N.P.L. photometric standard, and the stated uncertainty of 2% presumably includes any uncertainty in the realisation there of the international standard of photometry. We will proceed to compare the Kew measurements with the assumed and computed extraterrestrial values.

3. Attenuation of radiation by the cloudless atmosphere.

The main absorbers of solar radiation, and the only ones considered here, are O_3 and H_2O, with the possibility of absorption by any particulate matter which may be present (e.g. smoke, dust, "nuclei"). The scattering agents are air molecules and particulate matter. Molecular scattering may be computed: that due to the non-polar molecules is tabulated as "Rayleigh scattering", and we have used the transmission data of Smithsonian Tables p.431 in the present work. It has been found that even in the cleanest atmospheres there is attenuation of unabsorbed radiation in excess of the Rayleigh scattering. Fowle was able to correlate this extra scattering with the amount of water vapour in the atmosphere, he referred to it as "scattering by water vapour", and it is tabulated under this heading in Smithsonian Tables p.432. There is no theoretical support for this attribution, and the spectral distribution of this scattering has a form more consistent with a particulate than a molecular source, being appropriate to a broad distribution of particle size about a mean radius of 0.25 μ. We will compute this scattering by means of the Smithsonian transmission coefficients, but will refer to it as "Fowle scattering".

To compute the depletion of the direct solar beam by the clean atmosphere we proceed as follows. Taking the extraterrestrial radiation as specified by Nicolet in bands of 0.01 μ for wavelengths less than 0.75 μ, 0.05 μ from 0.75 μ to 1.50 μ, 0.10 μ from 1.50 μ to 2.00 μ, and 0.50 μ above 2.00 μ, compute the depletion due to ozone using the absorption coefficients of the Smithsonian Tables (p.429), supplemented at wavelengths greater than 0.60 μ by those of Craig (1950, p.23). Compute in turn the Rayleigh and Fowle scattering of the beam transmitted by ozone, using the Smithsonian Tables procedure. Finally determine the water absorption by means of Kimball's coefficients (Smithsonian Tables p.437), assuming all the absorption is at wavelengths greater than 0.70 μ. The errors in neglecting the scattering prior to O_3 absorption, and in considering the radiation absorbed by H_2O

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as not subject to prior depletion by scattering are negligible in the present context. The transmitted luminous flux in the direct beam follows by applying (1) to the transmitted direct radiation.

This computation has been made for a model atmosphere containing 2 mm O_3 and 2 cm precipitable water, for sinh 0.8, 0.4, and 0.2, where h is the solar altitude. This was chosen in the first place as being appropriate to several days in May 1948 which formed the first case treated. In view of the considerable computation involved, and the comparatively low precision of the measurements, this model has been taken as representing average conditions, and is used as a standard atmosphere in this report.

4. Angular distribution of scattered light - a working hypothesis.

To complete the comparison of attenuation in a clean atmosphere with the observations we require a method of computing the diffuse radiation D, the downward component of the radiation scattered from the direct beam, which will depend on the sun's altitude and the angular distribution of the scattering. Fig.4 shows this distribution for red and green light for single scattering by particles of radius 0.025 μ and 0.5 μ (Hilsum 1948). The position is complicated by multiple scattering; it is reasonable to expect this to increase the backward scattering from an assembly of particles, as in the case of cloud. We recall that the present measurements of the direct beam, I, I_Y, and I_R, include radiation scattered forward within a cone of semi-angle about 5°, so that practically all the scattering from particles of radius about 1 μ or more is included in the direct rather than the diffuse radiation. Furthermore this radiation is excluded from D by the shade ring, the correction for which assumes uniform scattering over the whole sky. With this in mind we suggest, as a working hypothesis, that upward and downward components of the diffuse radiation, as measured, are equal. The hypothesis is sound (for different reasons) when applied to Rayleigh scattering and scattering by large ($r > 1\mu$) particles. In the intervening range, which presumably includes the cause of the Fowle scattering, the hypothesis fails to some extent, more seriously for high solar altitudes than for low. We suggest that the general coherence of the results shows that this failure is not serious, and is not likely to introduce discrepancies in computed D of more than about 1% of the extraterrestrial radiation. It should of course be understood that the apertures of the direct beam thermopiles and the shade ring were not chosen with this application in mind, but rather as the smallest which could conveniently be constructed and kept in alignment.

5. Procedure.

Our objects are

(a) to examine the material for internal consistency

(b) to see how far the measurements can be explained in terms of the assumptions concerning extraterrestrial radiation, transmission by the model atmosphere, and angular distribution of scattering

(c) to deduce the modifications necessary to bring the transmission properties of the model atmosphere into the closest possible agreement with observation.

We have used five independent methods of approach.

(i) Comparison of L and ($I_Y - I_R$).

The difference between I_Y and I_R gives the transmitted radiation within a band approximately bounded by $\lambda = 0.55\mu$ and $\lambda = 0.64\mu$, as may be seen from Fig.2. The maximum eye sensitivity (I.C.I. eye) lies at $\lambda = 0.555\mu$, and we may therefore expect transmission of luminous flux to be closely analogous to the transmission of ($I_Y - I_R$)

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which we will denote by I_X. According to our assumptions L is given by the extraterrestrial luminous flux (L ext.) less the ozone absorption (LO_3abs), less half the scattered illumination (L scat.) i.e.

$$1/2\ L\ scat. = L\ ext. - L\ O_3abs - L \qquad (2)$$

whilst half the scattered radiation between $\lambda = 0.55\mu$ and $\lambda = 0.64\mu$ is given by

$$1/2\ I_x\ scat. = 1/2\ I_x\ ext - 1/2\ I_x\ O_3abs - 1/2\ I_x \qquad (3)$$

Half the scattered radiation, expressed as a fraction of the extraterrestrial radiation, is according to our assumptions the albedo, if we neglect ozone absorption of the radiation scattered outwards.

This quantity, computed for the model atmosphere, is shown in Fig.5 together with the curves determined from the measurements by means of (2) and (3). More details of the experimental values are given in Table I and Appendix I. It is possible, owing to the different way in which the absorption enters (2) and (3), to explain the observed curves of Fig.5 by means of the computed curves for the model and the same additional absorption and scattering for both L and I_X. These additional values are listed in Table I. This treatment implies that the additional absorption and scattering is appreciably independent of wavelength in the region between about 0.50μ and 0.65μ, and that the scattering satisfies our assumptions regarding angular distribution. The true albedo is then to be computed from (2) and (3) having regard to any additional absorption.

(ii) Comparison of the extraterrestrial radiation on a horizontal surface (Esinh) with the sum of T, D, and the known absorption.

On our assumptions D is equal to the radiation scattered outwards from the atmosphere, so that the sum of D, T, and the absorption should be equal to Esinh. Fig.6 shows T, D, and the absorption computed for the model atmosphere, expressed as fractions of Esinh, the mean of all readings being used. The sum falls short of Esinh by a fraction which can be accounted for only by additional absorption. The additional scattering is given by the difference between the observed values of D and those computed from the model, which are also shown on Fig.6. The additional scattering and absorption derived in this way is shown in Table II. It will be seen that we have computed absorption of the direct beam only, absorption of the downward scattered radiation has been neglected. Adjustment of this might change the values of the additional absorption and scattering by 1% or 2% of Esinh but not more.

(iii) Comparison of monthly totals of I, I_Y, I_R, and D.

The attenuation of the direct beam, and of those portions passed by the filters, was computed from the model for a range of solar elevations. Monthly totals of hourly values of I, I_Y, and I_R were available and the sunshine record S gave the fraction of each hour for which the direct beam had been observed, and hence the monthly total of extraterrestrial radiation against which to compare the tabulated values. Mean values of solar altitude appropriate to the month and hour were used. Such a mean is unreliable at low solar altitude, and since the sunshine record also fails at an appreciable value of I (about 15 mw cm^{-2}) the method was not applied for hours with mean solar altitude less than 10° ($\sin h < 0.175$). Two months, May and December 1948 were treated, the readings used being set out in Table III.

Tables IV and V give, for wavelength ranges $\lambda < 0.55\mu$ (i.e. $I - I_Y$) and $\lambda < 0.64\mu$ (i.e. $I - I_R$) respectively, the monthly totals of extraterrestrial radiation in the various ranges of sin h, the observed transmitted radiation, and the attenuation computed from the model. The final columns show the radiation unaccounted for, as a fraction of E, and as a fraction of the extraterrestrial radiation in the wavelength band. It is not possible

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from the present data to divide this into scattered and absorbed components. Table VI shows the corresponding figures for the whole spectrum. In this case the extra attenuation may be divided approximately into scattered and absorbed components by using values of D appropriate to the month and solar altitude. D values measured on cloudless occasions during May and December 1948 are shown in Table VI; the additional scattering is twice the difference between D and half the model scattering ("computed D").

(iv) Examination of I, I_R, T and D for selected hours.

A number of occasions had been noted as "cloudless" in the original tabulations of I_Y and I_R, the implication being that a careful scrutiny had disclosed no trace of cloud, including cirrus. This rarely occurs at Kew. On several of these occasions a standardisation of some or all the thermopiles had been made, so the records could be considered more than normally reliable. Several of these occasions, to which the check equality $T = I\sin h + D$ applied within about $\pm$ 2% were examined individually in the following way. $(I - I_R)\sin h$ and $I_R \sin h$, the radiation in the direct solar beam for $\lambda < 0.64\mu$ and $\lambda > 0.64\mu$, were taken, and added to the appropriate values of absorption, and upward and downward scattering computed from the model. The additional attenuation for the two bands was obtained by taking this sum from the appropriate extraterrestrial value, and this was divided between absorption and scattering (assumed the same up and down) by adjusting the total downward scattering to give the observed D, leaving the absorption by difference. The treatment is analogous to that of para.5(iii). The results are set out in Table VII, which shows the various components of the radiation in mw cm^{-2}. It will be noted that a small adjustment has been made to the downward component of the Rayleigh and Fowle scattering, to allow for absorption in the lowest layer of the atmosphere. The two occasions in May 1948 contain the means of observations made during corresponding hours on five successive days of a settled spell of exceptionally cloud free weather; the other occasions are for individual hours.

(v) Extrapolation of $I_Y - I_R$ to zero air mass.

The radiation in the band defined by $I_Y - I_R$ is, in the model atmosphere, subject only to the small Chappuis band absorption of ozone. We may regard it as approximately monochromatic, and expect its attenuation to conform to Beer's law, so that a plot of log $(I_Y - I_R)$ against air mass (cosec h) should be linear, and should yield the extraterrestrial radiation in the wavelength band when extrapolated to zero air mass, so long as atmospheric conditions remain steady during the period of observation. The difficulty is, of course, to find periods with steady conditions. The measurements were examined and periods chosen where observations had been obtained during four or more consecutive hours, or over at least a fourfold air mass range. (These periods were not necessarily cloudless). A plot of log $(I_Y - I_R)$ against cosec h was made, and all those occasions were retained on which a straight line could be drawn without straining the imagination. Many occasions could of course be rejected even before plotting. Only twelve suitable occasions were found in an 18 months record. The choice was subjective, but we can see no way of avoiding this. The plots were extrapolated to zero air mass. (Graphically; it was thought that the precision of the measurements, with regard to systematic errors, was not such as to justify least squares computation). The results, corrected to mean solar distance, are shown in Table VIII, and a selection of the plots in Fig.7. Nicolet's value of the extraterrestrial solar energy in the band passed by the filters is 16.85 mw cm^{-2} (See Appendix I). The agreement with this value is remarkable, having regard to the fact that the measurements are on the Ångstrom scale and should be increased by about 1% for comparison, but the mean deviation, though smaller than we would expect from our knowledge of the measurements, shows that no very useful contribution has been made to the problem of the solar constant. Nevertheless the evidence is not completely negligible, and supports our assumptions. By more elaborate and precise, but fundamentally similar and not more numerous, actinometric measurements in the less variable atmosphere of Davos, Schuepp (1949) has also advanced a "high" estimate of the solar constant.

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6. Discussion of results.

(i) The mutual consistency of the observations.

The additional scattering and absorption computed by the methods of Section 5 are collected in Figs.8 and 9. The division between "visual" and "infra red" for method 5(iv) is at the cut-off of the OR1 filter $\lambda = 0.64\mu$, whereas "visual" for method 5(i) refers approximately to the band $\lambda = 0.50\mu$ to $\lambda = 0.64\mu$.

The most reliable estimates may be expected from method 5(ii). This involves the greatest quantity of homogeneous material (all cloudless occasions in 5 years), and the measurements of T and D are well standardised and least subject to known systematic error. The full lines on Figs.8 and 9 have been drawn through these results. Method 5(iv) also uses the well standardised selected readings of, so far as total scattering and absorption are concerned, only two instruments. The results should be reliable but would be expected to show considerable scatter by reason of the great variability of atmospheric transmission on individual occasions. This scatter would be expected to be increased in the separate "visual" and "infra red" estimates by the employment of a third observation I_R. These expectations are confirmed by Figs.8 and 9; the individual results are entirely consistent with the mean results of method 5(ii), but show some scatter about the mean lines. Method 5(iii) has the disadvantage of using the sunshine trace S to determine the fraction of the extraterrestrial radiation employed. With high sun and broken cloud such traces notoriously overestimate the duration of bright sunshine (it is possible to interpret the standard instructions for reading the trace as a positive invitation to overestimate). With low sun and heavy pollution the card might not be burnt at a time when I and I_R are still satisfactory records and an underestimate would result. An error in S would not affect the additional scattering determined by method 5(iii) (unless it were a very serious underestimate), but would be accumulated in the additional absorption, which is determined as the residue of attenuation after other sources have been accounted for. The scattering estimates are based on D for two or three cloudless days in the month combined with I and S for the whole month; this inhomogeneity might be expected to lead to larger errors in the additional scattering estimated by this method than by methods 5(ii) and 5(iv). Examination of Figs.8 and 9 again confirms these expectations; the derived additional scattering is reasonably consistent with the other estimates, with more scatter, the additional absorption is systematically high for the May results and systematically low for December, by amounts up to 10%. The overall agreement with the other methods is certainly as good as could be expected.

The situation with regard to method 5(i), involving L, is less satisfactory. The total attenuation shown in Table I is in reasonable agreement with the total attenuation in the visible given by method 5(iv), and with the total attenuation in the regions $\lambda < 0.55\mu$ and $\lambda < 0.64\mu$, given by method 5(iii) and set out in Tables IV and V. On the other hand the attribution of this attenuation entirely to a scattering process is not in accord with the direct evidence of method 5(ii), nor with the most reasonable interpretation of the results of the other methods. It is not possible to explain the discrepancy by changes in our assumptions regarding the model atmosphere, the computed attenuation, the angular distribution of scattering, or the extraterrestrial radiation, without at the same time decreasing the agreement between the other methods. The results are however very sensitive to systematic changes in L and we have computed the result of decreasing L by 5%. The resulting additional absorption and scattering are shown in Table IX and have been plotted in Figs.8 and 9. They are now in excellent agreement with the other values.

Blackwell (1953), discussing the illumination record, estimated that the mean figures should be accurate within ±5%. They have been subjected to considerable adjustments for known errors in the original tabulations, and are clearly less reliable than any of the other records we are concerned with here.

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There is little external material with which to compare them, what there is suggests that they may indeed be high. Blackwell has computed the 'luminous efficiency of daylight' from them, and his figure for cloudless conditions is the highest we have seen reported. The only comparable series of measurements of which we have found a record is that of Lopukhin (1953) at Tashkent, a locality probably less subject to smoke but more subject to dust haze than Kew. His results for cloudless conditions are shown in Fig.10; they are 5% to 10% less than Blackwell's.

To summarise: our measurements and assumptions form an internally consistent scheme with the exception of the measured illumination, which falls in line with the rest if reduced by about 5%, a figure which is just within the previously estimated limits of accuracy. The scheme implies that there is considerable absorption and scattering of solar radiation by a constituent, presumably particulate, of the cloudless atmosphere at Kew, which does not figure in our model. We recall that the model is based on known gaseous causes of attenuation with the addition of the imperfectly understood scattering observed by Fowle in clear mountain atmospheres. The postulated 'additional absorption' would be reduced if our accepted value of the solar constant were to be reduced (retaining Nicolet's relative spectral distribution): our only evidence against this is contained in the results of 5(v).

(ii) The additional attenuation.

Some further comments can usefully be made on the contents of Tables IV, V, VI, VII and IX, and Figs.8 and 9. We note first that all methods suggest that the absorption is about the same in the visual and infra red, and that its variation with solar elevation is qualitatively as expected. Its mean value is probably rather less than 10%. It is interesting to compare this "grey" absorption with the "additional radiation" found by Robinson (1947, 1950) in measurements of the atmospheric radiation at Kew. This increased the computed radiation by up to 10% i.e. up to possibly 6 or 7% of the black body radiation at surface temperatures, a result entirely consistent with the present measurements if we are concerned with a true grey absorber in the lower layers of the atmosphere.

The additional scattering also appears to be approximately "grey" in character. Method 5(iv) (Figs.8 and 9) suggests rather higher scattering in the visual than the infra red, and method 5(iii) (Tables IV, V and VI) suggests a maximum in the additional attenuation between $\lambda = 0.55\mu$ and $\lambda = 0.64\mu$, but the differences are small compared with the uncertainties of measurement and interpretation. A feature of the scattering curves which deserves comment is the nature of the variation with solar altitude. We have, except very roughly in applying method 5(iv), ignored absorption of the scattered radiation, both in computing the 'model' attenuation and in examining the results. This can have little effect with high solar elevations, but is probably already an important factor for sinh = 0.2. The 'model' scattering would be overestimated, and since, in all methods except 5(i), the additional scattering is arrived at by subtracting this model scattering from D, the additional scattering would be underestimated.

It is interesting to examine the day to day variation of the additional attenuation, and the observations provide several opportunities. The most convenient arises in the computation of transmission in the band $\lambda = 0.55\mu$ to $\lambda = 0.64\mu$ which is used in method 5(i). Fig.11 shows the distribution of the fractional transmission for sinh = 0.3 to 0.4 and sinh = 0.7 to 0.8, together with the model transmission. The very wide distribution is notable, and we see that the minimum (model) transmission is rarely approached. In spite of the fact that there is quite a high probability of 5% errors in individual transmission factors only one observation of the 750 used in preparing Fig.5 fell below the model value and that by no more than 1%. We may conclude that some additional attenuation is a universal feature of the atmosphere at Kew, even with the clearest air; it is therefore almost

/certainly

certainly a normal feature of the atmosphere everywhere in this country. The low transmission "tail" of the distributions of Fig.11 is undoubtedly the dismal effect of the London pollution.

We cannot from the observations find the corresponding frequency distribution for the additional absorption alone. There is no obvious reason why this should not be similar to Fig.11, but Robinson (1947) found a different type of distribution in his measurements of the atmospheric emission. This comprised a sharp peak of about 10% of all observations very near the estimated "model" value, with a fairly uniform tail to higher values. The emission observations are however too few in number, and the "model" emission too speculative a quantity, for any great weight to be laid on the results. It seems natural to attribute the additional scattering and absorption of solar radiation and the additional emission of long wave radiation to the same cause - natural and artificial nuclei, larger particles of smoke and dust, and undetected cloud, particularly cirrus. The scattering is however postulated to be at the same time approximately grey and approximately isotropic, so it cannot be explained in terms of single scattering by dielectric spheres. Multiple scattering, as in a thin cloud layer, scattering by irregularly shaped particles, or specular reflection, must be invoked.

(iii) Estimated albedo of the cloudless atmosphere.

The fraction of the incident flux of radiation returned by the cloudless atmosphere to space without change of wavelength, the albedo, follows immediately from our assumptions and the previous results. We have collected some values in Fig.12. The most important quantity meteorologically is the total albedo; on our assumptions this is merely the diffuse radiation expressed as a fraction of the extraterrestrial. This is curve 3 of Fig.12. We will term the fraction of the extraterrestrial solar illumination returned to space the "photometric albedo", to distinguish it from the albedo for radiation in the visible wavelength band, which is termed, by Fritz and others, the "visual albedo". The photometric albedo is given by the method of 5; and on the assumption that the measured L values are high by 5% is given by curve 1 of Fig.12. As we have seen, the photometric albedo cannot be deduced from our measurements by a completely self consistent argument if the L values are correct: according to the particular inconsistency adopted values ranging between ±4% of the curve of Fig.12 can be obtained without adjustment to the measured L. Method 5(i) allows an estimate of the albedo in the range $0.55\mu \leq \lambda \leq 0.64\mu$, which is also shown in Fig.12. The albedo in the ranges $\lambda \leq 0.64\mu$ and $\lambda \geq 0.64\mu$, from the results of Table VII is also shown, the latter range gives an indication of behaviour in the infra-red. Fig.12, of course, contains no new material, it is merely a combination of the material of Fig.9 with the computed scattering of the model atmosphere.

The albedo of a cloudless atmosphere is of interest mainly as part of the material necessary for computation of the planetary albedo by methods similar to those of Fritz (1951) and Houghton (1954). The interest of the results of Fig.12 is therefore limited by the fact that they refer to the special case of the London atmosphere. The method is likely to be of more interest in showing the possibilities of routine radiation recording. The present results show an unexpectedly high additional scattering, and Lopukhin's (1953) Tashkent observations cannot yield a very different value from ours. We therefore suggest that examination of other radiation records on similar lines would be interesting and possibly rewarding.

Appendix I

Measurement of the direct solar radiation transmitted by filters

Except for insertion of the filters the apparatus used to measure I_Y and I_R was similar to that used for I. These notes describe only the procedure necessitated by the use of filters.

The transmission factors are shown in Fig.2. They were determined at the N.P.L. in March 1950, i.e. after completion of the observations which have been discussed. They are in close agreement with the maker's specification for new filters, and it seems clear that deterioration of the type noted by Shulman (1943) was not serious. The N.P.L. certificate remarks "The accuracy of the measurement was limited by the quality of the filters to $\pm 1\%$", which confirms that there was no gross deterioration in use.

The first step in reduction of the measurements to give I_Y and I_R is the determination of the "equivalent sharp cut-off", at a wavelength λ_o given by

$$0.90\int_{\lambda_o}^{0.7\mu} d\lambda = \int_{o}^{0.7\mu} T_\lambda d\lambda$$

where T_λ is the fractional transmission at wavelength λ . For OY2 this cut-off is at $\lambda_o = 0.553\ \mu$, for OR1 it is at $\lambda_o = 0.641\ \mu$. For a given spectral distribution of radiation $I(\lambda)$ a factor to convert transmitted (measured) radiation into radiation in the required wavelength range incident on the filter is given by

$$\int_{\lambda_o}^{\infty} I(\lambda)d\lambda \Big/ \int_{o}^{\infty} T_\lambda I(\lambda)d\lambda$$

For an ideal filter, with a step-function transmission curve, this factor is independent of the distribution $I(\lambda)$. The two filters used have excellent properties and the factor does not vary appreciably within a reasonable range of assumed distributions $I(\lambda)$. For that proposed by Shulman (1943) - the direct solar beam after transmission through unit air mass of dry atmosphere - the factor for OY2 is 1.133 and for OR1 1.136. A factor of 1.13 has been used for both filters.

The quantity used in Section 5(i), I_X, is the difference of the energies incident on the filters in the two wavelength ranges transmitted. To obtain this from the difference of the measured energies a factor

$$\int_{0.553\mu}^{0.641\mu} I(\lambda)d\lambda \Big/ \int_{o}^{\infty} (T_Y - T_R)I(\lambda)d\lambda$$

must be employed, where $I(\lambda)$ is the distribution of incident energy. For the extraterrestrial $I(\lambda)$ this factor is 1.128, and a value of 1.13 has been used.

/TABLE I

TABLE I

Comparison of transmission for illumination and for radiation $0.55\mu < \lambda < 0.64\mu$ (Method and notation of section 5(i)). All radiation values are % extraterrestrial.

Sinh	Illumination		$0.55\mu < \lambda < 0.64\mu$		Additional absorption	Additional scattering
	$\frac{1}{2}$ L scat.	No. of observations	$\frac{1}{2}$ I_X scat.	No. of observations		
0.1 to 0.2	42.5	7	33.5	66	7	16
0.2 to 0.3	34.5	40	31	114		
0.3 to 0.4	34	97	28.5	118	1	28
0.4 to 0.5	27.5	81	25.5	92		
0.5 to 0.6	27	83	23	109	0	26
0.6 to 0.7	22.5	67	21	95		
0.7 to 0.8	20	77	18.5	87	0	20
0.8 to 0.9	17.5	42	17.5	68		

TABLE II

Additional absorption and scattering of the total solar radiation. (Method and notation of section 5(ii)). % Extraterrestrial radiation.

Sinh	0.8	0.6	0.4	0.2
Additional absorption	6	8	12	15
Additional scattering	10	10	8	4

/TABLE III

TABLE III

Observed Totals of I, I_Y, I_R (joules cm^{-2}) and S (hours).

Month	LAT.	Mean Sinh	I	I_Y	I_R	S	Direct extraterrestrial radiation during periods of bright sunshine (E x S)	I - I_Y	I - I_R
May 1948	11 - 13	0.832	8630	6460	5390	33.7	16190	2170	3240
	13 - 14								
	10 - 11	0.790	8920	6920	5740	34.8	16740	2000	3180
	14 - 15								
	9 - 10	0.713	8550	6500	5540	34.5	16580	2050	3010
	15 - 16								
	8 - 9	0.603	7580	6140	5300	34.1	16400	1440	2280
	16 - 17								
	7 - 8	0.472	7240	5740	5040	34.3	16480	1500	2200
	17 - 18								
	6 - 7	0.325	5750	4970	4360	32.5	15620	780	1390
Dec. 1948	11 - 13	0.244	2990	2620	2300	19.1	9820	370	690
	13 - 14								
	10 - 11	0.185	2170	1960	1710	15.0	7720	210	460

TABLE IV

Attenuation of direct radiation $\lambda < 0.55\mu$. Entries are % of total extraterrestrial intensity except where stated. (Method of Section 5(iii)).

Month	Mean Sinh	Model atmosphere			Observed transmission	Additional attenuation	Additional attenuation as % waveband
		Absorption	Scattering	Transmission			
May 1948	0.832	0.7	8.8	17.7	13.4	4.3	16
	0.790	0.8	8.8	17.6	12.0	5.6	21
	0.713	0.9	9.3	17.0	12.6	4.4	16
	0.603	1.0	10.2	15.6	8.8	6.8	25
	0.472	1.1	13.6	13.5	9.1	4.4	16
	0.325	1.3	15.9	10.0	5.0	5.0	18
Dec. 1948	0.244	1.6	17.9	7.7	3.6	4.1	15
	0.185	1.9	20.0	5.3	2.8	2.5	9

/TABLE V

TABLE V

Attenuation of direct radiation $\lambda < 0.64\mu$. Entries are % of total extraterrestrial intensity except where stated. (Method of Section 5(iii)).

Month	Mean Sinh	Model atmosphere			Observed transmission	Additional attenuation	Additional attenuation as % waveband.
		Absorption	Scattering	Transmission			
May 1948	0.832	1.4	10.8	28.7	20.0	8.7	21
	0.790	1.6	11.0	28.3	19.0	9.3	22
	0.713	1.7	11.7	27.5	18.2	9.3	22
	0.603	1.9	13.4	25.6	14.0	11.6	28
	0.472	2.1	16.0	24.8	13.5	11.3	27
	0.325	2.4	20.1	18.4	8.8	9.6	23
Dec. 1948	0.244	2.7	23.0	15.2	7.0	8.2	20
	0.185	3.2	25.6	12.1	6.0	6.1	15

TABLE VI

Attenuation of direct radiation. Entries are % of total extraterrestrial intensity. (Method of Section 5(iii)).

Month	Mean Sinh	Model atmosphere				Observed D	Observed transmission	Additional attenuation	Additional scattering	Additional absorption
		Absorption	Scattering	Transmission	D ($= \frac{1}{2}$ scattering)					
May 1948	0.832	12.0	13.3	74.7	6.7	10.9	53.4	21.3	8.4	12.9
	0.790	12.1	13.8	74.1	6.9	11.0	53.4	20.7	8.2	12.5
	0.713	12.4	14.9	72.7	7.5	10.3	51.6	21.1	5.6	15.5
	0.603	13.0	16.9	70.1	8.5	12.0	46.3	23.8	7.0	16.8
	0.472	14.1	20.2	65.7	10.1	13.2	44.0	21.7	6.2	15.5
	0.325	16.9	26.3	56.8	13.2	13.7	36.6	20.0	1.0	19.0
Dec. 1948	0.244	16.5	31.0	52.5	15.5	19.0	30.5	22.0	7.0	15.0
	0.185	17.6	36.0	46.4	18.0	23.0	28.0	18.4	10.0	8.4

/TABLE VII

TABLE VII

Analysis of direct and diffuse radiation on a horizontal surface for selected hours (Method of Section 5(iv)). Values are hourly means in mw cm^{-2} except where stated.

Date	LAT.	Mean Sinh	Wavelength range (μ)	Extraterrestrial I sinh	Observed I sinh	Observed D	Model atmosphere					Additional			
							O_3 Absorption	H_2O Absorption	Rayleigh and Fowle Scattering		Absorption	Scattering		Absorption % Ext.	Scattering % Ext.
									up	down		up	down		
12 March 1948	12 - 13	0.565	≤ 0.64	32.8	16.2		1.6	-	5.4	5.0	2.2	1.2	1.2	7	7
			> 0.64	46.0	25.6		-	8.7	1.6	1.5	3.3	2.7	2.7	7	12
			total	78.8	41.8	10.4				6.5			3.9	7	10
12 March 1948	15 - 16	0.33	≤ 0.64	19.1	5.8		1.2	-	4.3	3.8	2.3	0.8	0.8	12	8
			> 0.64	26.9	12.1		0.1	6.2	1.2	1.1	3.3	1.4	1.4	12	10
			total	46.0	17.9	7.0				4.9			2.2	12	9
15-19 May 1948	8 - 9 / 15 - 16	0.61	≤ 0.64	34.3	14.6		1.7	-	5.5	5.1	2.8	2.3	2.3	8	13
			> 0.64	48.2	30.0		0.1	9.1	1.6	1.5	3.9	1.0	1.0	8	4
			total	82.5	44.6	9.9				6.6			3.3	8	8
15-19 May 1948	10 - 11 / 13 - 14	0.80	≤ 0.64	43.3	23.7		1.9	-	5.7	5.4	1.5	2.5	2.5	3	11
			> 0.64	63.1	42.0		0.1	10.7	1.5	1.4	2.5	2.4	2.4	4	7
			total	106.4	65.7	11.7				6.8			4.9	4	9

TABLE VII(Contd.)

Date	LAT.	Mean Sinh	Wavelength range (μ)	Extraterrestrial I sinh	Observed I sinh	Observed D	Model atmosphere					Additional			
							O_3 Absorption	H_2O Absorption	Rayleigh and Fowle Scattering		Absorption	Scattering		Absorption % Ext.	Scattering % Ext.
									up	down		up	down		
26 July 1948	08 - 09	0.62	<0.64	34.4	17.3		1.7	-	5.5	5.2	2.1	1.3	1.3	6	8
			>0.64	48.2	30.2		0.1	9.1	1.6	1.5	2.9	1.4	1.4	6	6
			total	82.6	47.5	9.3				6.7			2.7	6	7
26 July 1948	11 - 12	0.835	<0.64	46.8	26.6		2.1	-	5.7	5.2	3.7	1.8	1.8	8	8
			>0.64	65.7	42.0		0.1	11.2	1.6	1.5	5.3	2.0	2.0	8	6
			total	112.5	68.6	10.5				6.7			3.8	8	7
21 June 1949	12 - 13	0.875	<0.64	48.2	23.6		2.2	-	5.8	5.2	5.4	3.0	3.0	11	12
			>0.64	67.6	49.6		0.1	11.6	1.7	1.7	2.7	0.1	0.1	4	0
			total	115.8	73.2	9.8				6.9			3.1	7	5
21 June 1949	17 - 18	0.385	<0.64	21.3	3.3		1.3	-	4.6	3.9	3.7	2.2	2.2	15	21
			>0.64	29.9	17.1		-	6.7	1.3	1.2	2.5	0.6	0.6	8	4
			total	51.2	20.4	7.6				5.1			2.8	11	11

/TABLE VIII

TABLE VIII

Direct radiation in wavelength region λλ 0.553μ - 0.641μ (i.e. $I_Y - I_R$), extrapolated to zero air mass, in mw cm^{-2} on Angstrom scale.

Date	Extrapolated intensity	Correction to mean solar distance	Corrected intensity
12th March '48	16.7	0.990	16.55
23rd April '48	17.8	1.011	18.00
7th May '48	15.4	1.019	15.70
16th May '48	15.4	1.022	15.75
17th May '48 (a.m.)	16.1	1.023	16.45
17th May '48 (p.m.)	16.7	1.023	17.10
18th May '48	15.4	1.023	15.75
3rd June '48	14.9	1.029	15.35
7th June '48	15.4	1.031	15.85
26th July '48	17.5	1.033	18.05
27th July '48	16.6	1.033	17.15
26th Sept. '48	16.8	1.006	16.90
Mean and Mean deviation			16.55±0.7
Extraterrestrial rad.^{n} according to Nicolet (Smithsonian 1933 scale)			16.85

TABLE IX

Additional scattering and absorption (% extraterrestrial) computed by the method of Section 5; on the assumption that the tabulations of L are 5% too high.

Sinh	0.8	0.6	0.4	0.2
Additional absorption	9	9	11	18
Additional scattering	14	16	16	4

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FIG. 1 ILLUSTRATING THE EFFECT OF ATMOSPHERIC POLLUTION ON ILLUMINATION AT KEW.

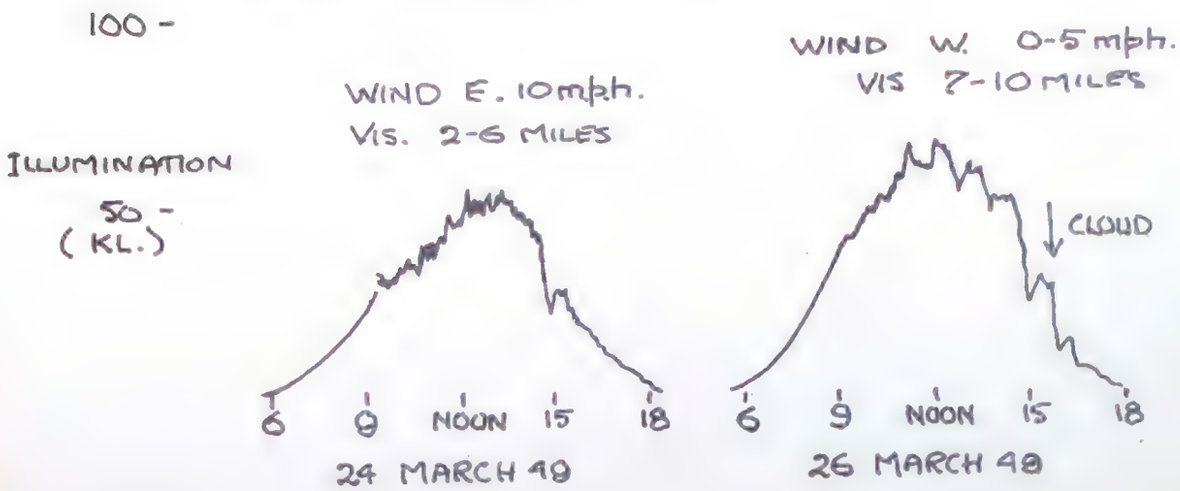


FIG 3 REFLECTION OF RADIATION FROM FILTER AND COVER GLASS.

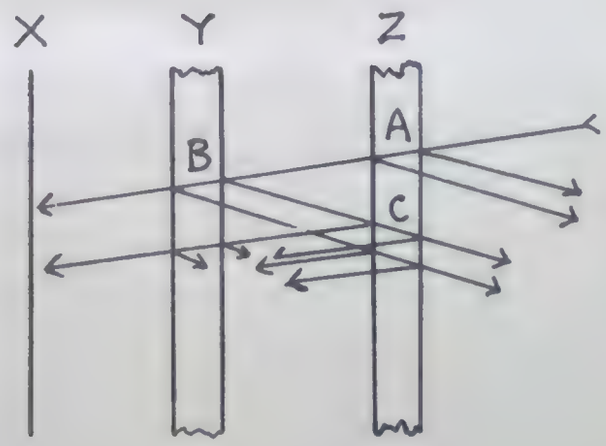


Fig 2. Transmission properties of the filters (at 20°c)

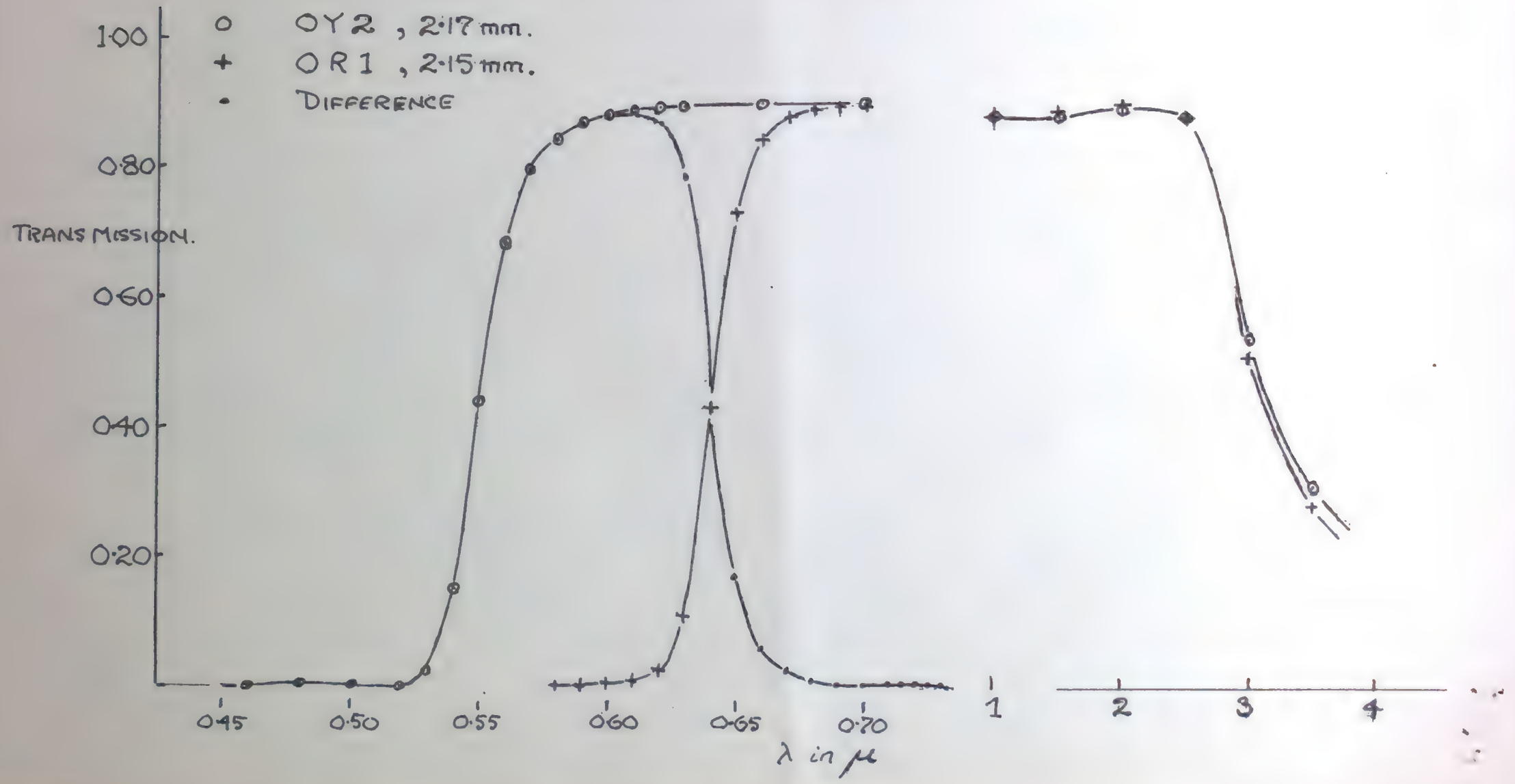
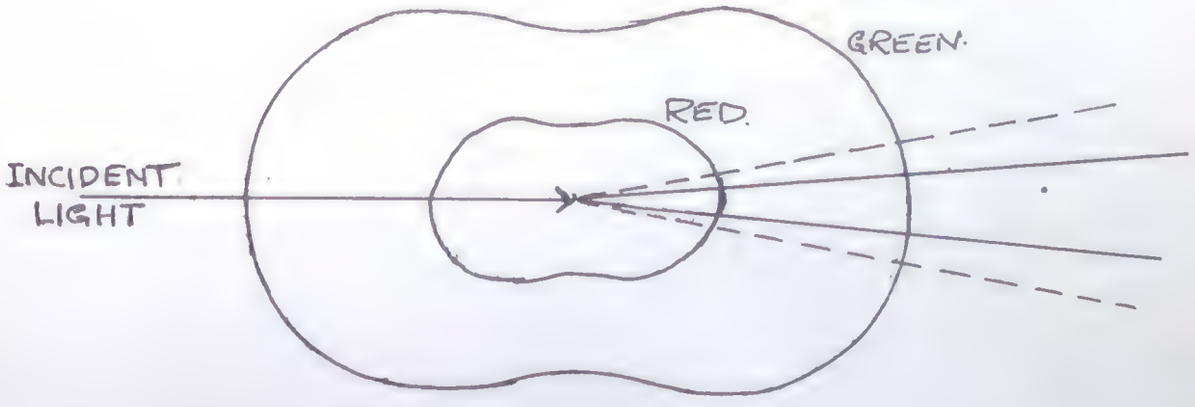
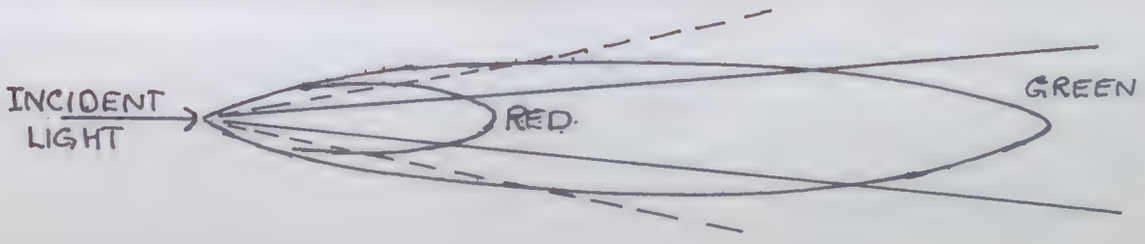


FIG 4. ANGULAR DISTRIBUTION OF LIGHT SCATTERED BY A SPHERICAL PARTICLE (HILSUM, 1948.)
APERTURE OF RADIOMETER IS SHOWN.

(a). RADIUS 0·025 μ.



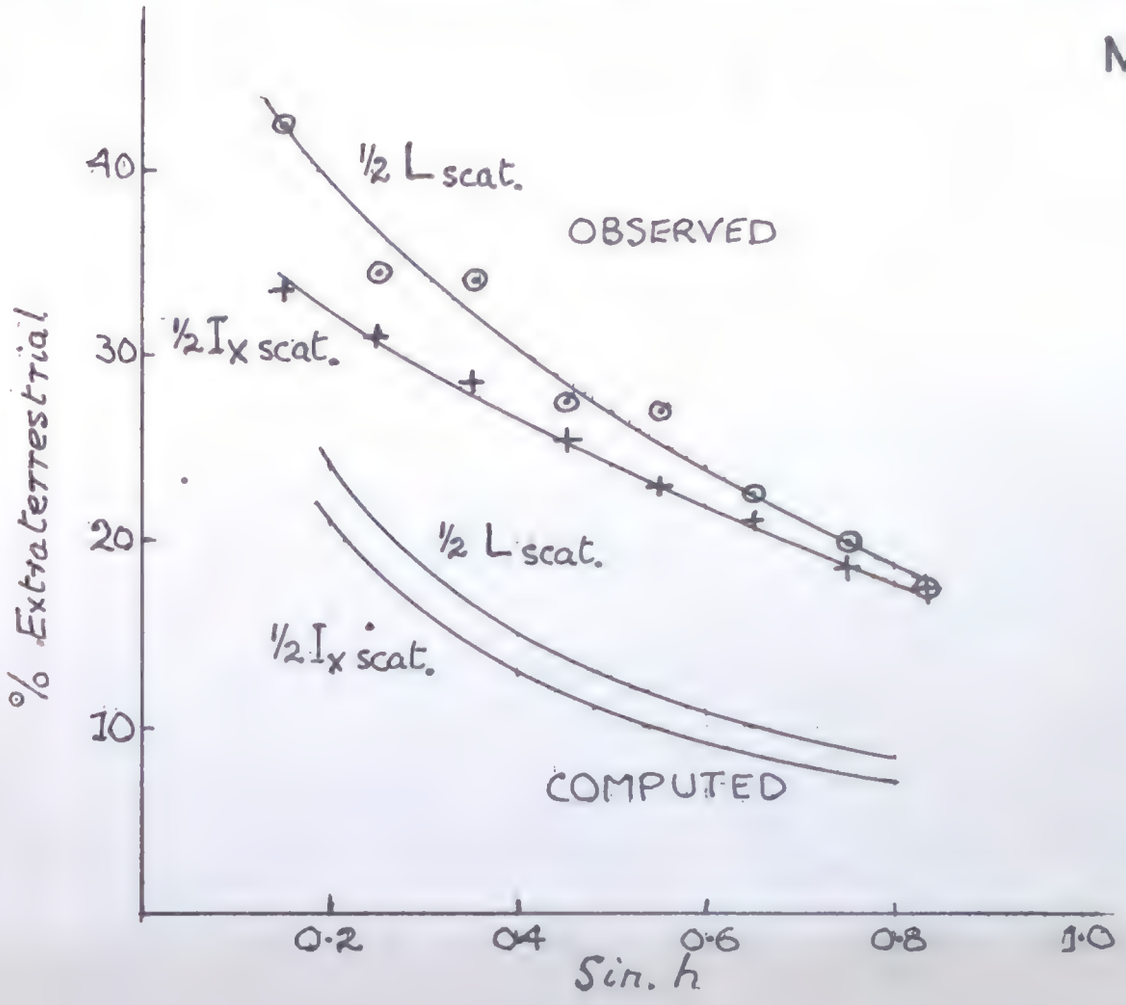
(b) RADIUS 0·5 μ.



SCALE OF (b) IS 3×10^7 x SCALE OF (a)

FIG 5 COMPARISON OF TRANSMISSION FOR ILLUMINATION AND FOR RADIATION IN RANGE $0.55\mu < \lambda < 0.64\mu$ METHOD AND NOTATION OF SECTION 5i

M.R.P. 894



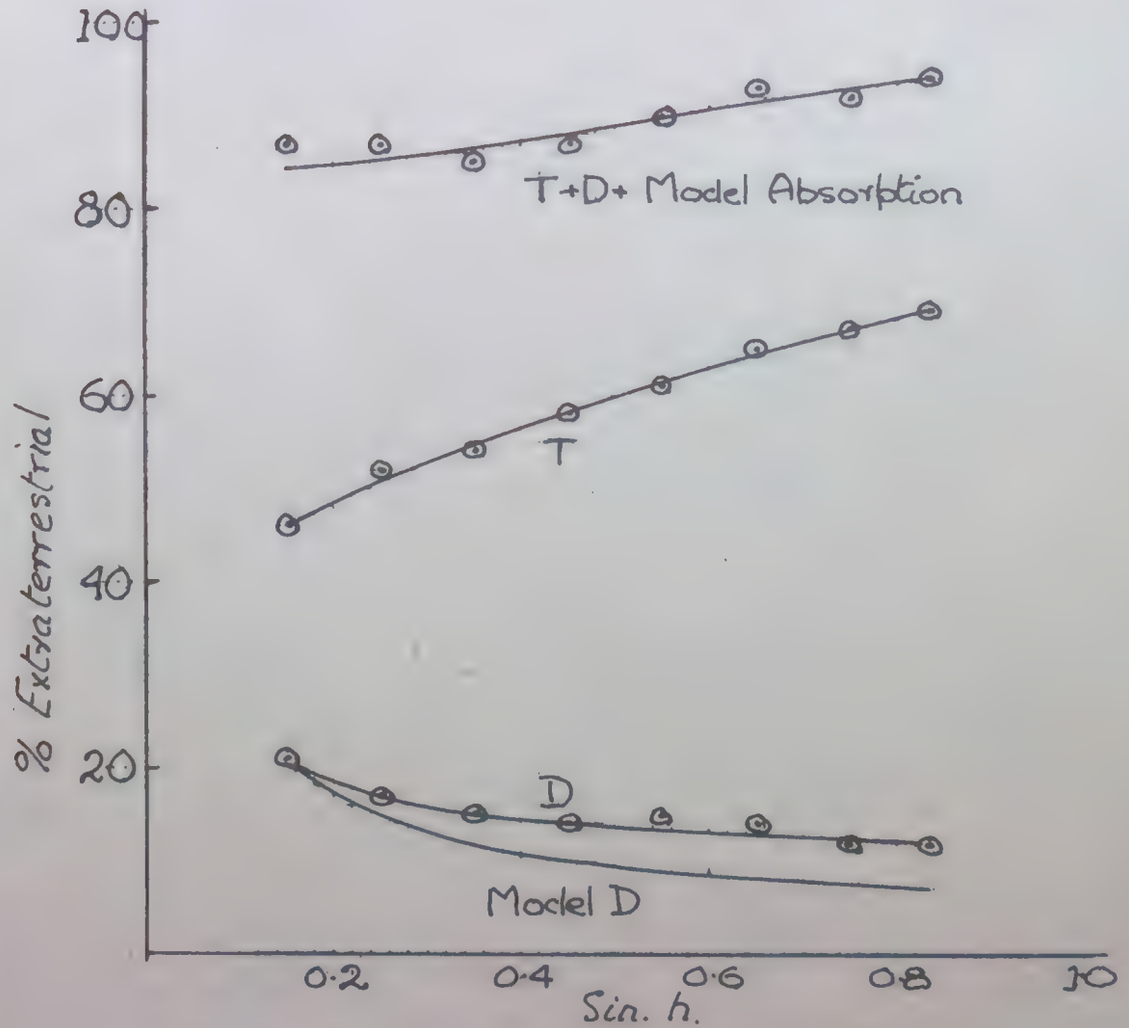


FIG. 6 ESTIMATION OF ADDITIONAL ABSORPTION AND SCATTERING. BY METHOD OF SECTION 5ii

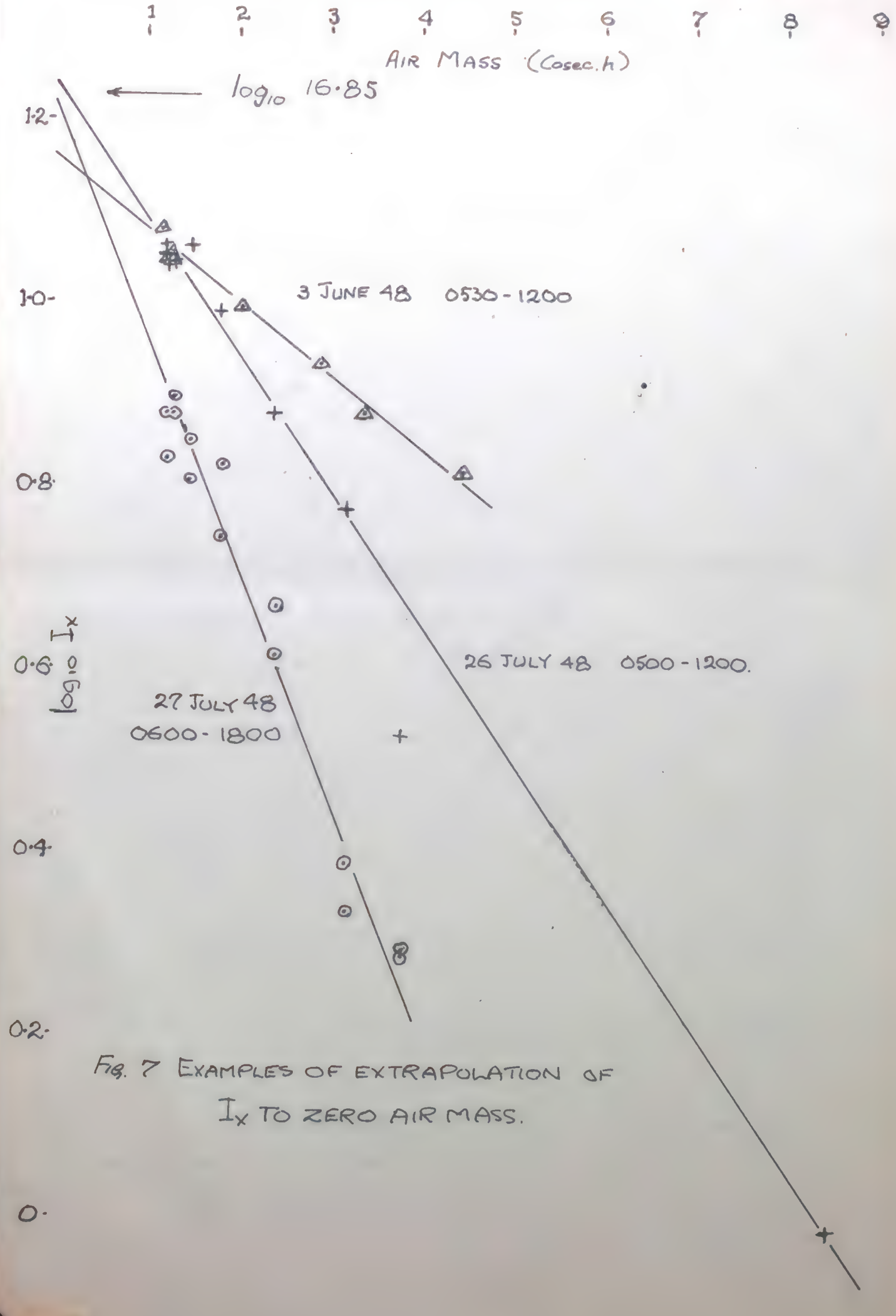


FIG. 7 EXAMPLES OF EXTRAPOLATION OF I_x TO ZERO AIR MASS.

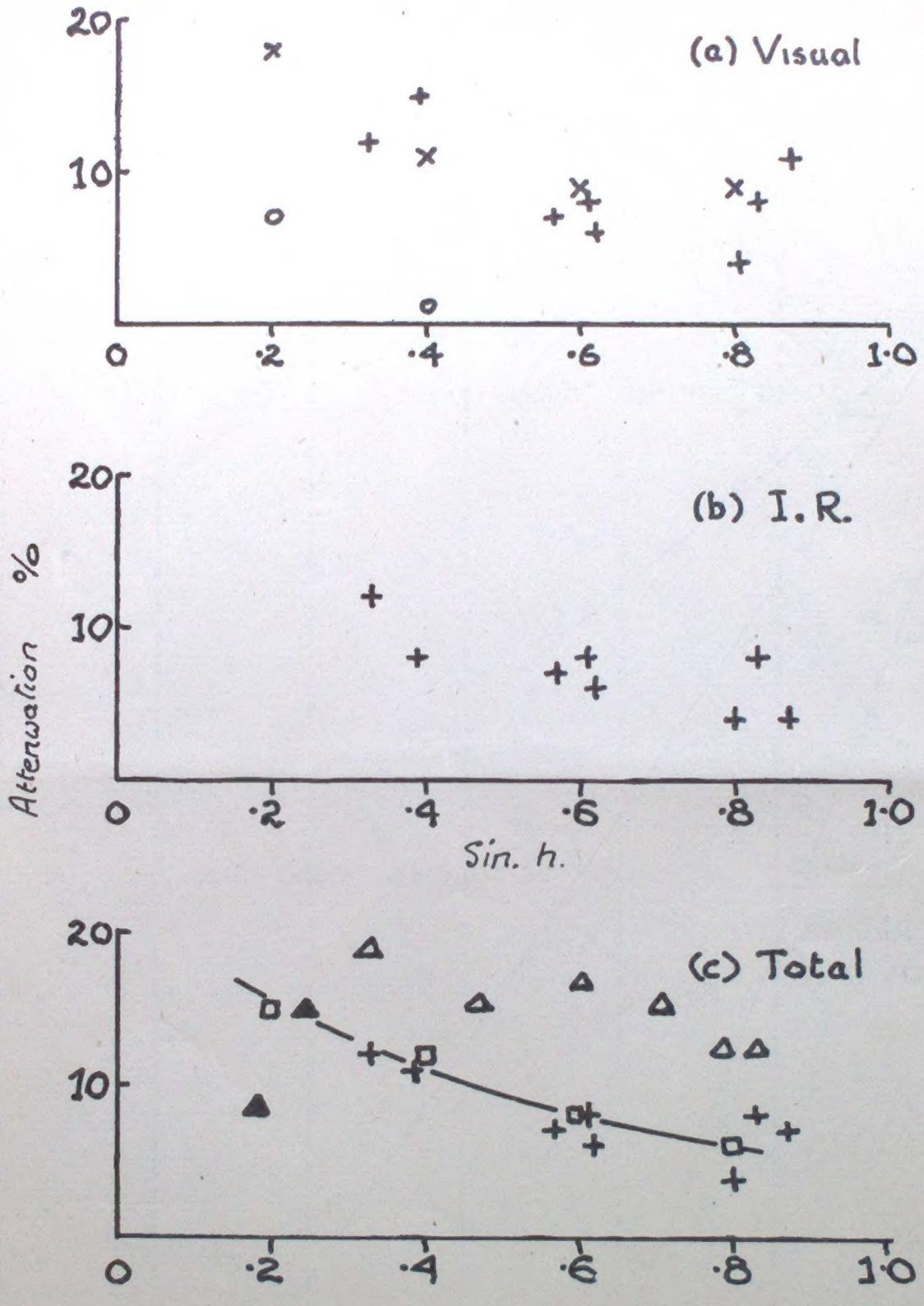


Fig. 8. The Additional Absorption

o Means of L and I_x (Method 5i)
x Means of 0·95L and I_x (Method 5i)
+ Individual values of I, I_R, and D (Method 5 iv)
□ Means of T and D, 5 years (Method 5ii)
△ Means of I and D, May 1948 (Method 5iii)
▲ . . . . . , Dec " " "

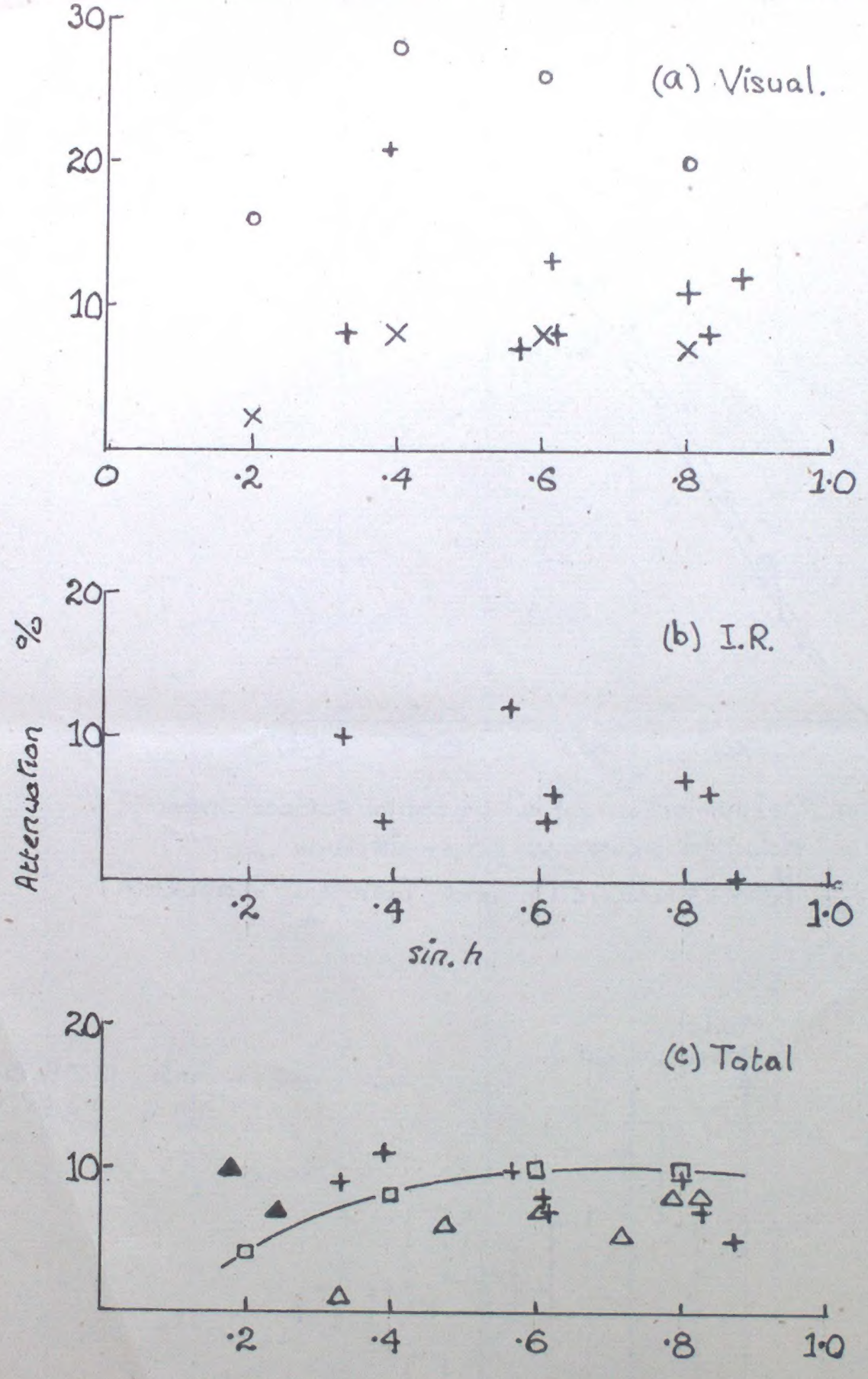


Fig. 9. The Additional Scattering

o Means of L and. I_x (Method 5i)
× Means of 0·95 L and I_x (Method 5i)
+ Individual values of I, I_R, and D (Method 5iv)
□ Means of T and D_5 5 years (Method 5ii)
△ Means of I and D, May 1948 (Method 5iii)
▲ Means of I and D, Dec. 1948 (Method 5iii)

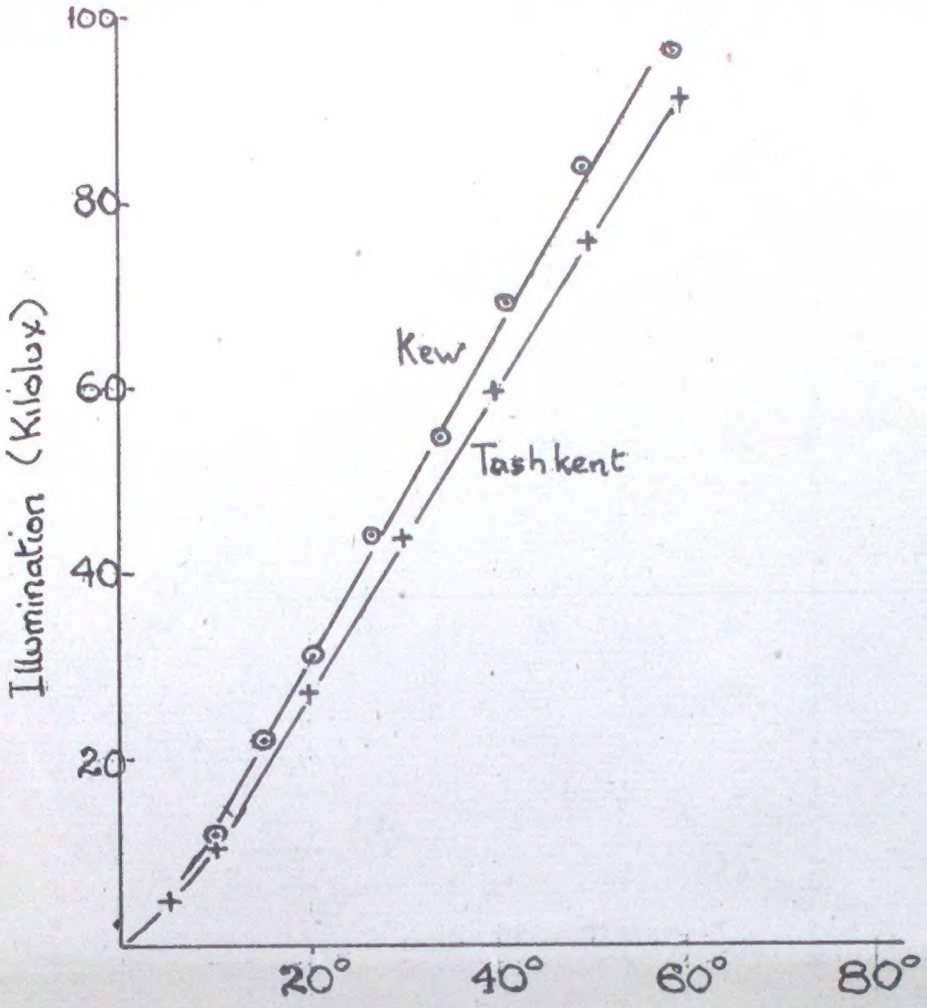


Fig. 10 Illumination of a horizontal surface under cloudless skies v. solar altitude
Kew (Blackwell) and Tashkent (Lopukhin)

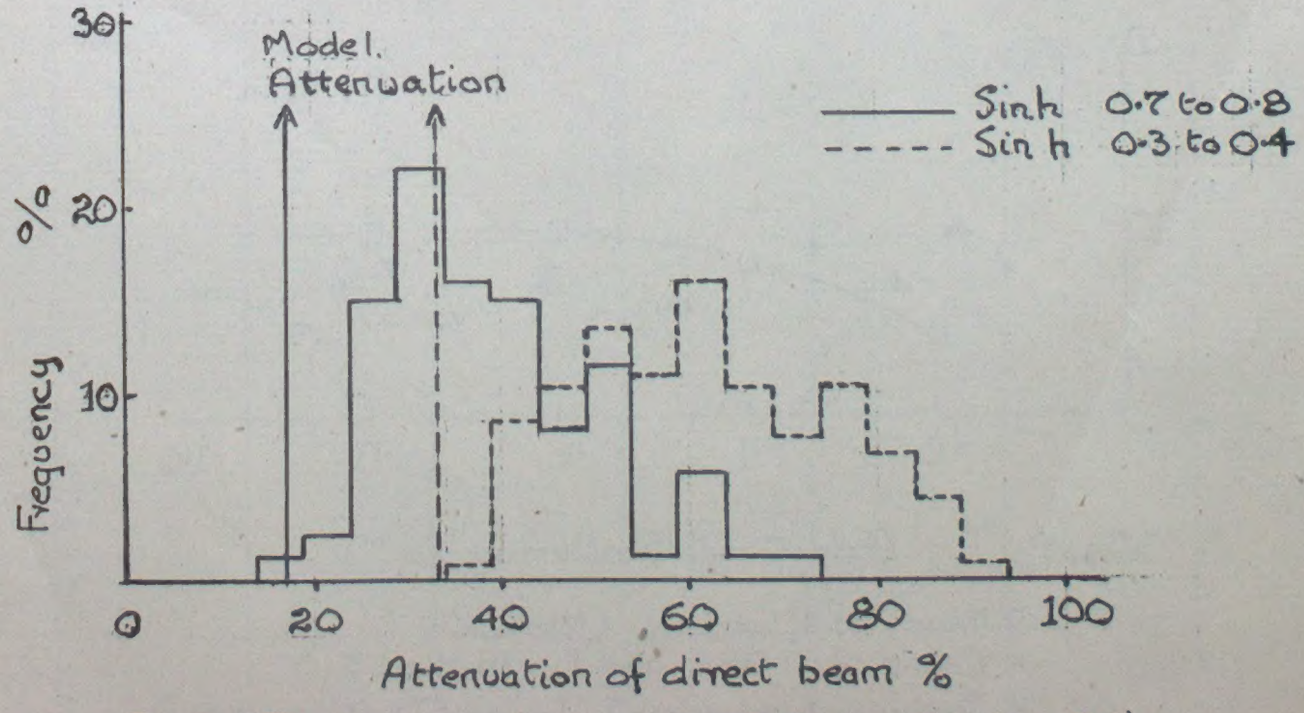


Fig. 11 Distribution of attenuation factor of direct radiation

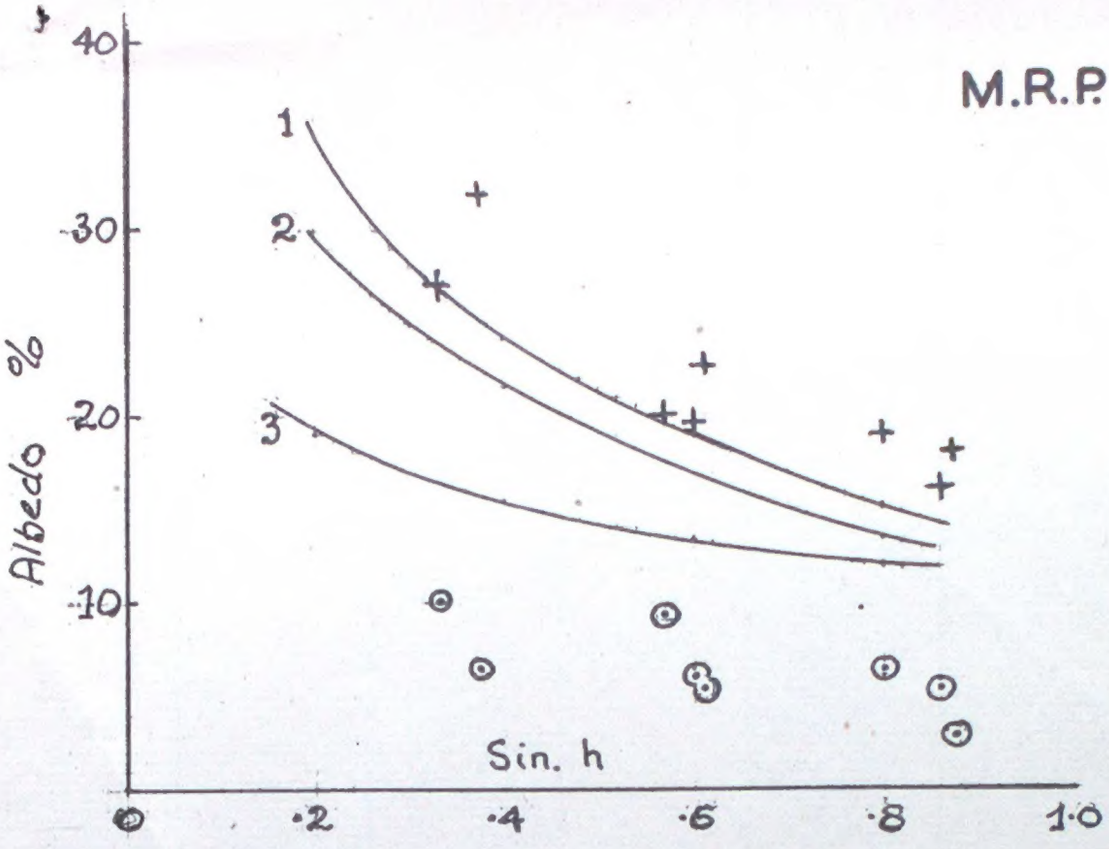


Fig 12 Albedo of the cloudless atmosphere at Kew

1 Photometric albedo

2 Albedo $0.55\mu < \lambda < 0.64\mu$

3 Total albedo

+ $\lambda < 0.64\mu$ } Selected occasions

⊙ $\lambda > 0.64\mu$ }